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MY SCIENTIFIC CONTACTS WITH V.E. LASHKAREV

To the 110-th anniversary of V.E. Lashkarev's birthday

1. Introduction. Personal Impressions

V.E. Lashkarev (1903–1973) is the famous scientist of Ukraine in semiconductor physics and its applied problems. The main achievements were obtained in the pioneer researches of the surface by LEED (low-energy electron diffraction) and the photoelectric properties of the bulk and the surface of semiconductors. The study of the thermoelectric effects on semiconductor surfaces led, in particular, to the world-level discovery: the first observation of a $p-n$ junction produced on the base of the heterostructure $Cu–Cu_2O–CuO$ (published in Izv. Acad. Sci. USSR, 1941). Structures with $p-n$ junctions are the base for the electron device industry till now.

I was acquainted with Academician Vadym Evgenovych Lashkarev (Fig. 1), an outstanding physicist of the 20-th century, in 1953, when he lectured a special course on the physics and the electronics of semiconductors to the students of the fifth year at the Faculty of Radiophysics of the Kyiv University. I was enlisted as a student of this new faculty in the middle of 1953, when the faculty was formed. Before, I studied at the Faculty of Physics of the same university. When the students were being distributed in groups according to their further specializations, I was selected by Academician S.I. Pekar into a theoretical group. To tell the truth, I was depressed of that because, since the second year of my study, I had been visiting, as a volunteer, semiconductor laboratories with vacuum posts, large electromagnets, technological ovens, in which young lecturers and senior students "baked" semiconducting oxides of all sorts and various colors: cherry, bright blue, black, green. Owing to that, I was presented to V.E. Lashkarev, who promoted my transfer to his chair. For me, this "escape" resulted in a very detailed examination (of about two hours) by S.I. Pekar in the course of lectures on quantum mechanics, with an excellent ultimate grade.

Just after my graduating from the University, V.E. Lashkarev included me together with my friend and classmate Vitalii Strikha to the staff of a prestigious, newly created special microwave laboratory; first, as an engineer, and, in half a year, as a senior engineer (besides a necessity to fill the vacancy, I already obtained a diploma cum laude).

I remember with gratitude how professionally and informatively V.E. Lashkarev conducted seminars,

Fig. 1. Academician of the Academy of Sciences of the UkrSSR V.E. Lashkaryov

how he taught us to make a quality review of scientific journals by proposing articles on new achievements in transistor physics and engineering. The students enthusiastically listened to his comments and advices, learning the high culture of communication and the respect to people of various statuses. I became even more sure of that, when I worked at the mentioned laboratory of the University. Vadym Evgenovych supported what he considered as new and important. But he could also reject, without regrets, all unessential that only took his attention away.

Hence, my work at the University passed at the microwave laboratory headed by V.E. Lashkarev. His deputy was a bit older than we were (by two academic years) Nataliya Mykolaivna Omelyanovs'ka, a very intelligent and benevolent woman. In due time, this unique laboratory was headed by Vitalii Illarionovych Strikha, who founded an original and promising direction of researches, the physics of real contacts metal–semiconductor. Of course, the laboratory staff also included other specialists and attendants: I. Radzievskyi, G. Zarubin, the laboratory assistant Darya Mykhailivna (a very modest woman), and others.

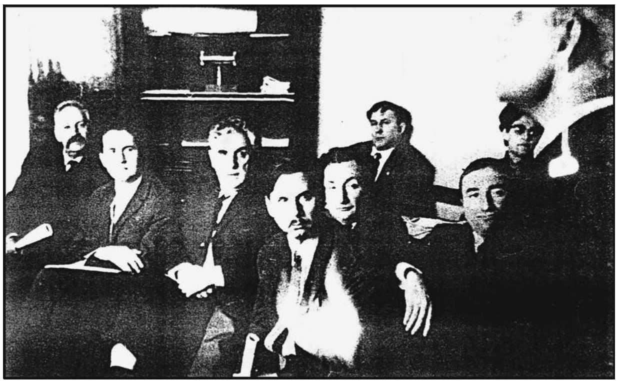

Fig. 2. At the scientific seminar in V.E. Lashkarev' office (1960). From left to right: V.I. Lyashenko, G.V. Lashkarev, I.M. Dykman, V.G. Litovchenko, M.K. Sheinkman, G.A. Fedorus, K.D. Glinchuk, N.B. Lukyanchikova, and V.E. Lashkarev

2. Researches in the Physics of the Surface of Semiconductor Microwave Detectors Headed by V.E. Lashkarev

I was charged to study the electric properties of germanium and silicon substances used to fabricate point-contact microwave detectors. Vitalii Strikha, who became my colleague at that time, was made responsible for the measurements and researches of parameters of those diodes, rectifiers for radars. A little older Revolt Mykolayovych Bondarenko dealt with technological problems. In other words, our microwave laboratory had been working at full capacity practically since its foundation, and this was achieved, first of all, owing to a large influence of V.E. Lashkarev, one of the most skilled semiconductor researchers in the world. For about a year and a half, under optimum conditions for creative activity, I, in cooperation with the colleagues from this new microwave laboratory V.I. Strikha and V.M. Dobrovolskyi, carried out two cycles of works: 1) on the physics of the surface in point-contacts of semiconductors with a metal electrode, i.e. in microwave point-contact diodes, and 2) on the physics of doping in "industrial" semiconductors, germanium and silicon. Those results were among the first (some of them, the first) ones obtained in the physics of industrially important semiconductors. In particular, this concerns our researches of the real surface of semiconductors, a directions in the solid state physics that only began to develop at that time.

Figure 2 exhibits a photograph made at one of the scientific seminars headed by V.E. Lashkarev at the beginning of the 1960s, where I took part as an active participant. I would like to attract attention to a considerable number of young scientists, which were actively involved by V.E. Lashkarev into discussions at his seminars.

It should be noted that the researches by V.E. Lashkarev in the semiconductor domain (the thermoelectric, photo-electric, and x-ray properties) began as early as in 1939–1941, at the Institute of Physics of the Academy of Sciences of Ukraine and at the Kyiv State University. Wide-gap semiconductors, mainly with the direct-gap structure and a large contribution of ionic bond (CuO, Cu_2O, ZnO, Fe_2O_3, SeO_x oxides, Ag_2S_3, and others), were studied. The surface properties were first studied using mainly plane contacts metal–semiconductor by V.E. Lashkarev together with the skilled physicists V.I. Lyashenko and G.A. Fedorus, and the results obtained were published in 1938–1941 in such well-known physical journals as *Zhurnal Teoreticheskoi i Eksperimental'noi Fiziki*, *Izvestiya Akademii Nauk SSSR*, and others. At that time, V.E. Lashkarev carried out an excellent cycle of researches on the condenser photo-

Fig. 3. Head of the Division, Corresponding Member of the NAS of Ukraine Prof. V.G. Litovchenko

emf and the thermal emf in the point contact. The latter researches brought V.E. Lashkarev in 1940 to his outstanding discovery, the barrier structure of $p-n$ transition that forms the basis of modern semiconductor electronics.

The researches by V.E. Lashkarev in the post-war years were also connected with direct-gap semiconductors. On the whole, these were photosensitive III–V semiconductors (CdS, CdSe, CaTe, InSb, and others). Nevertheless, the materials of applied electronics, germanium and silicon, i.e. semiconductors with the valence bond and the diamond-like crystalline structure, were not ignored. Intensive researches of Ge were stimulated by the discovery of "the surface transistor" (1947) fabricated on the basis of semiconductor structures with a plane, chemically etched surface with adjacent point contacts. An impetus to the study of the more chemically stable semiconductor, silicon, was given by the progress in the planar technology, as well as the creation of a field-effect transistor on the basis of the SiO_2–Si structure. The first silicon transistors were produced by Bell Labs. in 1957.

Below, I quote some results obtained at the mentioned microwave laboratory by the researchers N. Omelyanovs'ka, V. Litovchenko, V. Strikha, R. Bondarenko, and others in the co-authorship or under the direction of V.E. Lashkarev. In our first publications, we studied the properties of germanium and silicon surfaces in a point contact. A slow charge–discharge of surface states in the widely used microwave point-contact diode "bronze tip–chemically treated germanium surface" was described. A crucial influence of surface states on the barrier height and surface photoeffects – the condenser photo-emf and the conductivity of thin plates (the so-called field effect) – was revealed. Those experiments formed a basis for the formulation of the general trend of the microwave special laboratory for all the years to come.

Later, after I had entered the postgraduate study at the Institute of Physics of the Academy of Sciences of Ukraine in 1957, I studied the surface of germanium and silicon under the direction of Prof. Vasyl Ivanovych Lyashenko, the Deputy Head of the department. The results obtained were often and actively discussed together with V.E. Lashkarev. As an example, I recall the active participation of V.E. Lashkarev in the discussion of debatable issues initiated by Novosibirsk physicists (headed by A.V. Rzhanov) on the nature of surface photoeffects, the influence of the near-surface region of the space charge on the sticking of photo-induces carriers to the semiconductor surface, the peculiarities in the photoconductivity kinetics, the nature of photovoltaic effects under the condition of strong surface influence, the surface recombination, the discrete or continuous character of the energy spectrum of surface states, and so on. The discussion began in 1965 at the Scientific school on surface science (the base of Skalka, Uzhgorod University) and continued for some years. The end was put by V.E. Lashkarev's letter to A.V. Rzhanov, the director of the Novosibirsk Institute of Semiconductors. In this letter written after a detailed discussion with us, Vadym Evgenovych pronouncedly indicated the physical essence of the Kyiv group's position with respect to the nature of surface photoeffect and its differences from the bulk one. The key difference consisted in the localization of the captured surface charge and the formation of isolated surface barriers absent in the bulk case. V.E. Lashkarev diplomatically wrote "We came to a conclusion that our physicists adequately understand the physics of examined phenomena, and our misunderstanding with you, in our opinion, is most likely of terminological character".

3. Research of the Recombination Properties of Doped Germanium

The results obtained at the next stage of researches were published by V.E. Lashkarev and others in a cycle of publications in central academic physical journals, such as *Zhurnal Tekhnicheskoi Fiziki* (1957), *Fizika Tverdogo Tela* (1959), and *Ukrainskyi Fizychnyi Zhurnal* (1959). New results were reported concerning the doping of germanium with a shallow donor impurity of antimony (Sb, group V) and an acceptor impurity of beryllium (Be, group II). In particular, it was shown that those well-soluble impurities introduce shallow levels (centers), so that the bulk Fermi level shifts. The antimony impurity does not introduce additional recombination centers and enhances the recombination by changing the occupation degree, by charges, of the already existing "own" center, which may possibly be associated with the complexes of structural defects that arise at the crystal growth. At the same time, another scenario is realized for the beryllium impurity: in addition to the mechanism described above, beryllium atoms also introduce new recombination levels, being therefore not a desirable doping impurity.

The first paper was published together with V.E. Lashkarev in 1957 (V.E. Lashkarev, V.G. Litovchenko, I.M. Omelyanovskaya, R.N. Bondarenko, and V.I. Strikha, Dependence of the lifetime of foreign charge carriers on the concentration of antimony impurity in germanium, Zh. Tekhn. Fiz. **27**, 2437 (1957)). The main result of the paper consisted in that such a characteristic of the material as the lifetime of excited charge carriers plays an important role in the operation parameters of bipolar semiconductor devices. It was known that the introduction of impurity (e.g., nickel, iron, antimony, and some others) into germanium drastically reduces the lifetime value, but the nature of those variations had not been elucidated. In that work, the influence of antimony impurities was analyzed for the first time in a wide range of impurity concentration. As a result, we identified the origin of the charge-carrier lifetime variation.

In the work carried out soon under the direction of V.E. Lashkarev (V.E. Lashkarev, R.M. Bondarenko, V.M. Dobrovolskyi, G.P. Zubrin, V.G. Litovchenko, and V.I. Strikha, Properties of germanium doped with beryllium, Ukr. Fiz. Zh. **4**, 373 (1959)), we studied germanium doped with beryllium, the element of group II in the Periodic table of elements. Germanium crystals were grown using the Czochralski method. The fabricated single crystals of germanium had the specific resistance predicted by calculations. We also revealed a very high solubility of beryllium; namely, the maximum solubility of beryllium at the melt solidification temperature reached a value of 10^{19} cm^{-3}.

A detailed research of germanium doped with beryllium was described in the paper published in a new, at that time, central academic journal *Fizika Tverdogo Tela* (V.E. Lashkarev, R.N. Bondarenko, V.N. Dobrovolskii, G.P. Zubrin, V.G. Litovchenko, and V.I. Strikha, Electric and recombination properties of germanium doped with beryllium, Fiz. Tverd. Tela No. 2, 39 (1959)).

4. Conclusions

Let us summarize what was said above on the researches of the surface of and the recombination in germanium carried out under the direct supervision of V.E. Lashkarev.

1. An important influence of surface effects (the charging of surface levels, the presence of a transient dielectric layer, the variation of the potential barrier) on the operation characteristics of microwave point-contact diodes was established for the first time.

2. An original result was obtained for the doping of germanium with a shallow donor impurity of the group V element, antimony (Sb). This widely used impurity was demonstrated to form shallow doping donor levels rather than to stimulate the recombination. The recombination is induced by another center with a deep level of 0.22 eV, which is based on structural defects, the latter being always present owing to the accepted technology of germanium crystal fabrication (the Czochralski method).

3. The recombination properties of beryllium (Be), the acceptor element of group V, which is highly soluble in germanium, was studied for the first time. Beryllium was found to be a doubly charged impurity; hence, it could form two levels: a shallow one at $E_v = 0.07$ eV (doping) and a deep one at $E_v = 0.17$ eV (recombination).

4. A superhigh efficiency of the doping with beryllium owing to its high solubility (10^{19} cm^{-3}) was demonstrated. The mechanism of this effect was elucidated: beryllium atoms can easily occupy the lattice sites without inducing a substantial lattice deformation due to their small size ($r_a \sim 1$ Å).

The physical effects and research objects proposed by V.E. Lashkarev remain challenging till now and completely correspond to the world level of semiconductor science.

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